



Research article

Operationalizing the feedback between institutional decision-making, socio-political infrastructure, and environmental risk in urban vulnerability analysis



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ABSTRACT

Urban adaptation to climate change is likely to emerge from the responses of residents, authorities, and infrastructure providers to the impact of flooding, water scarcity, and other climate-related hazards. These responses are, in part, modulated by political relationships under cultural norms that dominate the institutional and collective decisions of public and private actors. The legacy of these decisions, which are often associated with investment in hard and soft infrastructure, has lasting consequences that influence current and future vulnerabilities. Making those decisions visible, and tractable is, therefore, an urgent research and political challenge in vulnerability assessments. In this work, we present a modeling framework to explore scenarios of institutional decision-making and socio-political processes and the resultant effects on spatial patterns of vulnerability. The approach entails using multi-criteria decision analysis, agent-based models, and geographic information simulation. The approach allows for the exploration of uncertainties, spatial patterns, thresholds, and the sensitivities of vulnerability outcomes to different policy scenarios. Here, we present the operationalization of the framework through an intentionally simplified model example of the governance of water in Mexico City. We discuss results from this example as part of a larger effort to empirically implement the framework to explore sociohydrological risk patterns and trade-offs of vulnerability in real urban landscapes.

1. Introduction

There is a growing concern among scientists and urban planners regarding the increasing vulnerability of megacities to climate-related hazards around the world (Chelleri et al., 2015; Ernstson et al., 2010; Henderson et al., 2016). In the context of adaptation to climate change, there is a persuasive tendency to focus on the biophysical drivers of vulnerability, such as precipitation extremes and storm surges, when considering investment in infrastructure (Hunt et al., 2017; Pelling, 2011).

Nevertheless, we know that vulnerability is affected by political decisions, motivated by influential actors (managers and elected officials). Such decisions are not made on the basis of a technical cost-benefit type of calculation alone; rather, they are grounded in social, cultural, political, and economic priorities of stakeholders (Pahl-Wostl, 2007). Large-scale public and private investments are thus influenced by contextual cues, social networks, political pressure, social norms,

and the legacy of prior decisions (Sivapalan et al., 2012; Smith et al., 2010; Wise et al., 2014; World Bank, 2015). The preferences of these actors can shape investments, resulting in material changes in the biophysical world, influencing risk perceptions and decision priorities. The nature of these priorities and their feedback within the biophysical landscape is what we refer to as socio-political infrastructure (Eakin et al., 2017).

The socio-political infrastructure associated with well-organized constituents plays a critical role in shaping political goals and agendas (Castro, 2004), particularly in times of elections and as part of long-term strategies for allocating social benefits (Jacobs, 2008). This is often the case when formal institutions are weak or distrusted, and citizen participation in decision-making is lacking (Scheffran and Battaglini, 2011). Under these conditions, manifestations of discontent may become a significant determinant of governance processes (Eakin et al., 2017). To improve urban risk management, it is therefore necessary not only to understand how the actions of influential actors are

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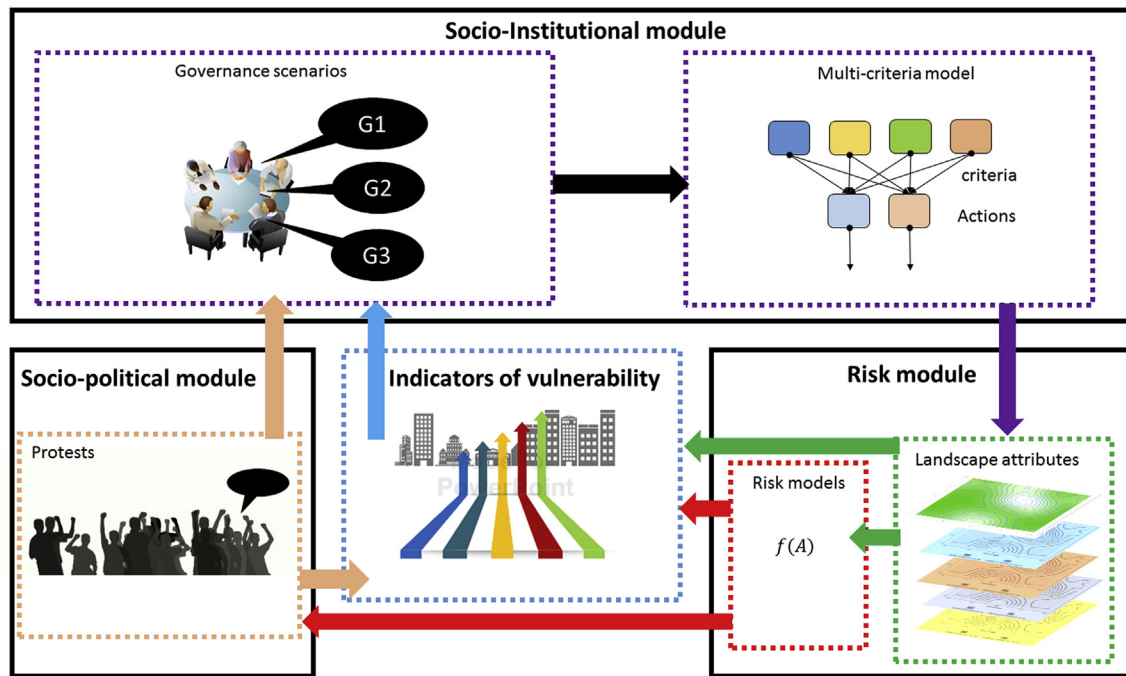


Fig. 1. Flow diagram of the modeling framework. The figure shows the three modules of the modeling approach to explore socio-environmental vulnerability. The approach places emphasis on the feedback between decision-making (socio-institutional), environmental and infrastructure-related risk (risk module), and the socio-political module (residents). The socio-institutional agents make decisions under different governance scenarios (G1, G2, and G3). These scenarios are defined by a set of criteria, priorities, budget, and actions; the outputs of the socio-institutional model are investments in selected areas. The infrastructure systems, in synergy with the biophysical context and other attributes of the landscape, determine the risk and hazard events that result in vulnerability and indicators. The outcomes contribute to the socio-political landscape that can influence socio-institutional agents when making decisions, along with the risk models. When the socio-political infrastructure module is connected to these socio-political responses, the system results in a feedback loop.

made and expressed spatially, but to acknowledge the continual, coupled dynamics between socio-political and biophysical processes (Biggs et al., 2015, 2012; Eakin et al., 2017; Pelling, 2011; Seto et al., 2017).

Social and political scientists have developed computational models that consider the socio-political forces involved in institutional decisions (Nordhaus, 1975), for instance, voting behavior and formation of coalitions based on election cycles (Fowler and Smirnov, 2005). Researchers interested in socio-political movements have also represented algorithmically people's discontent with institutional decisions (riots, protests, and violence) (Epstein, 2002; Lemos et al., 2013), providing insights on why and when people engage in manifestations. Geographers have also developed computational models to understand protests and manifestations in relation to the physical features of neighborhoods and human decisions (Torrens and McDaniel, 2013). Increasingly, the use of agent-based models (ABM) is providing a new way of representing the mechanisms that lead to a social uprising, often linking those processes to the decisions of authorities (Lemos et al., 2013). Consequently, ABMs offer new possibilities for simulating complex socio-political decisions (Akhbari and Grigg, 2013; Barthel et al., 2010; Galán et al., 2009).

And yet, researchers have to incorporate these socio-political decision models into formal analyses of urban vulnerability. Vulnerability assessments usually focus on risk from an engineering or climate perspective. Social factors, however, are often static and derived from socio-demographic data (Pahl-Wostl, 2003). Scientists have a large range of modeling tools to represent risk based on biophysical determinants, but we lack a modeling framework to incorporate the rich literature of socio-political models (Seto et al., 2017). Therefore, there is a gap in the research literature between the large number of models and tools that the different research communities have to understand the factors affecting social outcomes, and the lack of frameworks available to integrate sociopolitical and biophysical factors into vulnerability assessments (Eakin et al., 2017). We argue that we can start

making progress to create tools for vulnerability assessments that incorporate the feedback between political factors and biophysical determinants of risk.

This work aims to contribute to filling this gap by operationalizing the association between vulnerability analysis and socio-political dynamics. We present a formal approach to couple models that integrate institutional decisions, socio-political responses, and biophysical determinants of risk. Our contribution is to operationalize the integration of these multiple factors in a dynamic and spatial framework for vulnerability assessments. The approach is based on combining, three well-established modeling techniques: agent-based modeling, multi-criteria decision analysis (MCDA) and geospatial simulation (Bojórquez-Tapia et al., 2001). MCDA refers to a set of techniques to implement robust decision schemes by considering multiple factors. MCDA provides an ensemble of analytical tools to characterize choices among alternatives based on preferences of actors, considering the causal relationships among a set of criteria and a set of alternatives (Ishizaka and Nemery, 2013; Kabir et al., 2014; Mendoza and Martins, 2006). Making these linkages explicit implies identifying the importance and values that decision-makers assign to the alternatives and criteria. Importantly, MCDA bases its utility on building decision models in consultation with stakeholders, enabling the development of empirically-based decision-making algorithms.

Agent-based modeling is a technique to model the actions of individual entities, and their interactions with other agents and the environment (An, 2012; Railsback and Grimm, 2012). In an ABM, agents are independent entities that make decisions based on a set of simple rules and the environmental context. From these interactions, patterns emerge that differ from the simple rules that determine individual decisions. ABMs can include geospatial data to represent responses of actors to changes in realistic biophysical and socio-political landscapes. We use ABM (Janssen and Ostrom, 2006) to represent socio-political dynamics in a geographical context. Geospatial simulation is used here

to link the decisions of the agents and the biophysical context.

We present this modeling framework using a stylized example resembling Mexico City: a megacity with socio-hydrological risk. In this example, a single institutional agent is making investments over time to improve the potable water and sewage infrastructure systems in the neighborhoods of the stylized landscape. The example includes a socio-political model to simulate protests from residents in response to their vulnerabilities (Fig. 1). This theoretical example is a morphism of an empirical model to simulate and explore the hydrological vulnerability of Mexico City with stakeholders and managers of the water sector (Bojorquez-Tapia et al., 2019). Our final goal is to develop an exploratory model to facilitate the self-reflection and self-evaluation of the practice of decision-makers under different scenarios of climate change and socio-political and institutional decision-making. The results of the stylized example, therefore, should serve to illustrate how the outcomes of these models should be presented to provide meaningful information to the stakeholders that are represented in the model as agents.

2. Methods

In this section, we first provide an overview of the integrated framework, followed by its mathematical formalization and operationalization. Then, the stylized model is presented with results. The mathematical and computational details of the implementation are presented in the [Supplementary material Notes 1, 2 and 3](#). In every section, we emphasize the close collaboration with stakeholders that is needed to develop models.

2.1. An overview of the integrated modeling framework

The framework is composed of three modules: a risk module, a socio-political module and a socio-institutional module (Fig. 1). The risk module contains the biophysical models that simulate the exposure to hazards. Here, the distribution of exposure to hazards is simulated using geospatial simulation and frequency-based risk of hazards, and the attributes of the landscape that influence risk must be represented spatially. Key to the framework is to find evidence to connect changes in attributes with the decisions criteria of the agents (alternatives of the MCDA model). Representing risk and exposure according to the heterogeneity of the landscape is critical for the operationalization of a decision tool for vulnerability assessment. Operationalization includes defining the minimal spatial unit of analysis, the extension of the area of governance, and the attributes of the landscape that the socio-institutional agents will use as criteria to select alternatives for investment. Spatial units refer to delimited units in space that are recognized by the institutional agents and therefore serve as markers for the distribution of investments. Examples of spatial units relevant for megacities are neighborhoods, census blocks, delegations, boroughs, and municipalities; nevertheless, these units could be any socio-political delimitation of the landscape that is used for the purpose of governing the territory.

The second module is socio-political. Here, social-political simulations – e.g., agent-based modeling – represent the socio-political responses of agents to their vulnerabilities. Local agents are simulated along with their socio-political actions (i.e., protests, riots, demands). In an empirical setting, the development of social-political models should be in coordination with stakeholders, through interviews, focus groups, and triangulated with media reports and other sources of information. Soft validation of the model should also be encouraged to make sure these processes are accurately defined and represented (see Shelton et al., 2018 for an example of soft validation in the context of Mexico City).

The final module is the socio-institutional, representing the decisions of institutions. Here, the operationalization refers to connecting decision algorithms (MCDA) with the consequences of the institutional

actions in the landscape attributes (Fig. 1). First, the institutional agents must be defined, then the decision criteria and decision options associated with these agents specified. The institutional agents are represented by a MCDA model, which is articulated as a network of criteria, variables and associated actions, and the valuation of each criterion and action according to how city managers evaluate its importance in relation to addressing a particular hazard. Each criterion is linked to the attributes of the landscape, which are associated with the landscape attributes. To connect the socio-institutional model to the risk models, the actions of the agents with respect to selected spatial units (i.e., the decision of the agent to make an investment in a census block) should modify the models in the risk module. The connection of the socio-political module with the socio-institutional module is made via the importance socio-institutional decision-makers give to socio-political processes such as protests by vulnerable residents (see socio-institutional module).

2.2. Formalism

In this section, we provide formal definitions for the components of the modules, the construction of governance scenarios, and the exploration of different indicators of vulnerability to communicate results to stakeholders.

2.2.1. Risk module

Risk-based models must be used to simulate the risk of exposure over space and time. Let's define an urban landscape as a group of spatial units with multi-attribute variation (altitude, the area covered by infrastructure, aged infrastructure). A spatial unit is indexed by the symbol j , with $j = \{1, \dots, J\}$. Each spatial unit is vulnerable to environmental hazards according to the risk. The risk of exposure to hazards is associated with the characteristics and condition of the landscape attributes; formally:

$$\varepsilon_{jt} \sim f(A_{jt}, \Omega), \quad (1)$$

where A_{jt} is a set of attributes of the landscape within a spatial unit, j , and Ω refers to the set attributes exogenous to the agents' actions (geographic, social, or climatic). Importantly, under this formulation, risk profiles across the city are influenced by the actors' actions.

2.2.2. Socio-political module

The socio-political outcome in our framework is an emergent property associated with the level of exposure, ε , the perception of the socio-political actors about the decisions made by the socio-institutional actors, y (see socio-institutional module), a level of tolerance to exposure, τ , and the motivation (m) of the actor to consider these factors. Formally, a socio-political outcome is denoted by the symbol δ , such that:

$$\delta_{jt} = f(\varepsilon, y, \tau, m), \quad (2)$$

where δ_{jt} is the outcome of a socio-political process in unit j at time t . The factors $\{\varepsilon, y, \tau, m\}$ should be associated to the level of adaptation of the socio-political actors to the conditions of their neighborhoods. These agents must be able to evaluate trade-offs about engaging in socio-political actions vs. investing time and resources to cope with and adapt to the environment they confront (Eakin et al., 2016; Shelton et al., 2018). These trade-offs are often linked to evaluations of landscape attributes that influence the tolerance of the agents to the exposure and to inaction by authorities. Therefore, we should expect the implementation of socio-political processes to incorporate routines for agents to learn and adapt.

2.2.3. Socio-institutional module

In this module, a model to simulate the decisions of the socio-institutional agents must be defined. Importantly, the information to

develop and parametrize these models must be obtained via consultation with stakeholders through formal and well-established techniques (Bojórquez-Tapia et al., 2011; Saaty, 2004).

Institutional agents must decide investments in the spatial units. The investments of the institutional actors are associated with a set of possible actions, $K = \{k_1, \dots, k_m\}$, that modify a set of infrastructure systems, $V = \{v_1, \dots, v_N\}$. Formally, an investment in unit j at time t for action k in system v is defined as a Boolean variable, $y_{jvt}^k = \{0,1\}$. When $y_{jvt}^k = 1$, a decision to invest in action k and infrastructure system v has been made in the spatial unit j at time t .

2.2.3.1. Scenarios of governance using MCDA models. A governance scenario in this framework is the set of criteria (C), priorities (W), actions, (K), and budget (B) that a socio-institutional agent has to define investments in infrastructure systems. Thus, a governance scenario G is formally defined as: $G: \{\{C_v^G\}, \{k_v^G\}, \{W_v^G\}, \{B\}, \{V\}\}$, where $\{C_v^G\}$, $\{W_v^G\}$, and $\{k_v^G\}$ are the set of criteria, criteria weights, and actions associated with scenario G , for systems v . It is important to note here that G is obtained from consultation with stakeholders using elicitation of mental models and multi-criteria analysis (see Bojórquez-Tapia et al., 2019 for an empirical demonstration).

The investment decisions by the socio-institutional agents are accomplished by two sub-routines: site suitability and site search. Site suitability informs the socio-institutional agents as to the best spatial units for investment, based on the criteria and alternatives of the MCDA model. The site search procedure then evaluates the different alternatives of spatial units in order to identify the best investment for the most optimal spatial units.

2.2.3.2. Site suitability. The goal is for the socio-institutional agents to allocate investments in the selected spatial units where they are most needed, according to a governance scenario defined by the MCDA model (see below). The computational goal is to obtain metrics of distance d_{jvt}^k that represent the distance from an ideal spatial unit. This ideal point represents a fictional, utopian spatial unit with the optimal conditions of landscape attributes associated with the decision criteria in the MCDA model of the simulated agent (Bojórquez-Tapia et al., 2011). Each spatial unit's suitability for investment is obtained through a process of multicriteria evaluation that takes into consideration the relative importance of the decision criteria:

$$d_{jvt}^k = \sum_i^I w_{iv}^G x_{ijvt}^k, \quad (3)$$

where d_{jvt}^k is the distance to the ideal point of the spatial unit j , with respect to action k and system v and w_{iv} is the criterion weight of criterion i related to system v from the set of criteria weights $W_v^G = \{w_{1v}^G, \dots, w_{iv}^G, \dots, w_{Iv}^G\}$. In equation 3, the value of the landscape attributes associated with the criteria are represented in a standardized form, x_{ijvt}^k . The value functions transform the natural scale of a criterion to a $[0, 1]$ value scale (1 represents the most undesirable state and 0 the most desirable state). Formally, a set of criteria, $C_v^G = \{c_{1v}, \dots, c_{iv}, \dots, c_{Iv}\}$, is associated with the set of value functions, $X_v^G = \{x_{1jvt}^k, \dots, x_{ijvt}^k, \dots, x_{Ijvt}^k\}$, such that $x_{ijvt}^k = f(c_{iv}, \varphi_i) \forall i \in I$. It is important to mention that the shapes of the functions must be elicited in consultation with the stakeholders. Therefore, this standardized score, x_{ijvt}^k , represents a judgment about the importance of an observable value of a certain criterion for the socio-institutional agent. It also represents the relationship between the magnitude of the geographic attribute in the landscape related to a criterion i and an action k in infrastructure system v at time t (Beinat, 1997). For the site suitability assessment, d_{jvt}^k , $0 \leq w_{iv}^G \leq 1 \forall i \in I$, and $\sum_i w_{iv}^G = 1$ for each scenario G and system v .

2.2.3.3. Site search. The decision to invest in infrastructure systems in selected spatial units, that is $y_{jvt}^k = \{0,1\}$, entails a suitability analysis through multi-objective site search (Bojórquez-Tapia et al., 2011; Cova and Church, 2000). Site search is invoked by choosing a single

investment, y_{jvt}^k , involving a specific action k (i.e., maintenance or replacement of infrastructure) for a number of spatial units that is established by budgetary constraints, B . Formally, the socio-institutional agents calculate the following expression

$$\text{maximize } F(y^k) = f(d_{jvt}^k y_{jvt}^k): \forall j, k, v \quad (4)$$

subjected to budget (B), which represents the maximum number of spatial units where the institutional agent can invest, and local constraints such as the number of possible actions in each cycle of a decision. Variables y_{jvt}^k are the $\{0,1\}$ mutually exclusive decision variables related to investment in infrastructure system v (equals 1, if the spatial unit j is selected for investment with action k for system v , or 0 otherwise). In this way, we can simulate the preferences of these agents for investing in the units where infrastructure is most needed according to their priorities.

2.3. Indicators of vulnerability

We expect the stakeholders represented to interact with these models, such that their policies and preferences can be self-evaluated. Thus, the results of the model should be summarized in a set of indicators of vulnerability. These indicators should describe the outcomes in terms of spatial patterns, thresholds and sensitivities, and trade-offs between the indicators. Therefore these indicators should summarize the dynamics of the vulnerability associated with the decisions of the agents.

2.4. Stylized example

We present a stylized or “lumped” model (Zeigler et al., 2019) to illustrate the integrated modeling framework. This lumped model is a morphism of an empirically-based model of Mexico City socio-hydrological vulnerability (Bojórquez-Tapia et al., 2019). This simple model simulates the decisions of two types of agents: a water authority and the group of residents. The water authority is part of the socio-institutional module, and residents are part of the socio-political module. The water authority invests in infrastructure systems to either increase the coverage or improve its condition. The only decision of residents is whether to protest (Supplementary material Note 1 and Note 3). In this example, spatial units are cells in a rectangular lattice. Each cell represents a neighborhood where residents live. These neighborhoods are located in a landscape with topographic complexity that maintains two essential characteristics of Mexico City's landscape: water scarcity and lack of services in the periphery highlands, and high risk of flooding and old infrastructure systems in the lowlands (Fig. 2).

For risk, we developed a purposely simplified representation of flooding and water scarcity using a risk function with only two independent factors: topography, and infrastructure condition (Supplementary material Note 1). The water authority's decisions entail solving the problem of where investments in infrastructure should be allocated (site search procedure) (Bojórquez-Tapia et al., 2011; Cova and Church, 2000). For the stylized example, only a single action per spatial unit is allowed. Under this constraint in the *site search*, it is sufficient to use a sorting algorithm. When this constraint is relaxed, other optimization methods are needed. The *site suitability* procedure requires the governance scenario as input (the MCDA model, Supplementary material Note 1). We generate only governance scenarios where the institutional agent considers four criteria per infrastructure system, three of which are technical: 1) the condition of the water and sewer infrastructure, 2) the number of neighborhoods covered by functional water and sewer infrastructure, and 3) the number of neighborhoods benefited by investments. A fourth criterion, social pressure, is non-technical and is operationalized as the number of protests by residents in a neighborhood (Supplementary material, Note 1). Residents respond to the water authority by protesting against the

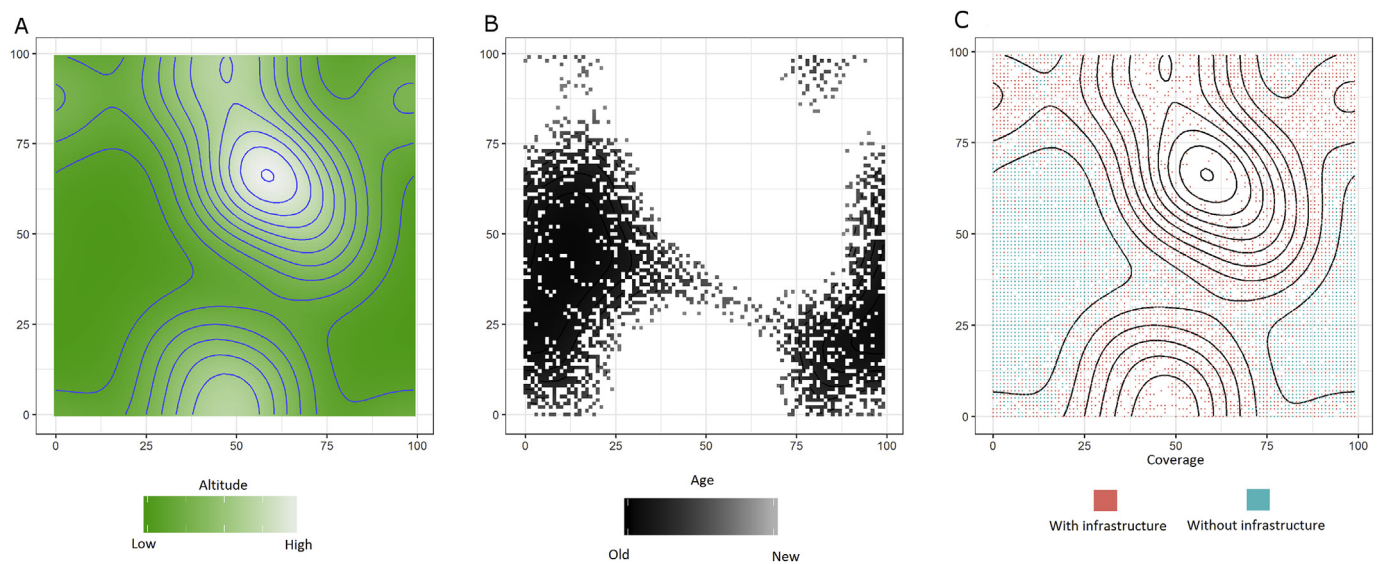


Fig. 2. The hypothetical urban landscape and initial infrastructure conditions. The figure shows the hypothetical landscape (Panel A), the initial age conditions of the infrastructure (B), and infrastructure coverage (C). These initial conditions are inspired by the characteristics of the urban landscape in Mexico City.

lack of investment and the level of exposure to water scarcity and flooding (Supplementary material Note 1).

We first simulated the risk model under three policies that differ solely on the importance the institutional agent gives to three technical criteria: In governance scenario 1, “Squeaky Wheel” (from “the squeaky wheel gets the grease”), prioritizes reducing social pressure by investing in the neighborhoods that protest the most. Governance scenario 2, “Expand Access”, the institutional agent gives more importance to constructing new infrastructure in neighborhoods where it is lacking. Governance scenario 3, “Repair First”, prioritizes the maintenance of existing systems by giving more importance to neighborhoods with aged infrastructure. The importance is represented by the value of the criteria weights, W_v^G (Supplementary material Note 1 and Note 3), but otherwise, the governance scenarios maintain the same network structure. The risk of hazards is the same in all governance scenarios, and it is simulated as a function of topographic and infrastructure conditions of the neighborhoods and a spatially uniform climate factor in the case of flooding (Supplementary material Note 1). Investments in maintenance or construction of new infrastructure modify the conditions for the provision of potable water and sewer system in the selected neighborhoods, which in turn influence the risk of hazard. Second, we compared the spatial and temporal patterns and trade-offs that emerge for different indicators of vulnerability (Supplementary material Note 2), under each governance scenario. We compared these scenarios with other optimal policies to show trade-offs. Finally, we conducted sensitivity analyses on key parameters where we expect to have high degree of uncertainty in an empirical setting.

3. Results

In this section, we describe results from simulating three designed governance scenarios and compare them against other possible scenarios. We also show how results can be presented graphically to convey meaningful information to stakeholders when presenting an integrated model. The way of graphically representing the results is based on feedback received from the experience of the authors in communicating with stakeholders. Specifically, we present results in three subsections: 1) spatial and temporal patterns, 2) governance trade-offs and 3) thresholds and sensitivity to governance. We focus on three indicators of vulnerability: 1) the condition and extent of infrastructure, 2) the number of protests per neighborhood, and 3) the level of exposure to flooding and water scarcity (Supplementary material

Note 2).

3.1. Spatial and temporal patterns

We first illustrate the distinct spatial patterns that emerge in the urban landscape under the three designed scenarios. We do this by showing patterns of infrastructure condition and expansion, exposure, and social-political outcome. We observed that the spatial distribution of risk and social pressure are “disturbed” by the different policies (Fig. 3). Under the Squeaky Wheel (SW), the spatial pattern observed for the potable water system is one of low expansion of new infrastructure into the periphery and high levels of investment into high altitude neighborhoods that are already equipped with infrastructure (Fig. 3). SW generates an old infrastructure system for potable water at the center of the urban landscape since more protests related to water scarcity should occur by default at the periphery. SW is the most effective of the designed policies in reducing protests in the city overall (Fig. 4b), and in the high-altitude areas in particular, which are those that suffer the most from water supply scarcity (Fig. 5). However, this governance produces the least amount of spatial coverage of functioning infrastructure systems overall (Fig. 4c and Supplementary material Fig. 2c).

The Expand Access governance, in which investments are heavily located in neighborhoods that lack infrastructure or have very aged infrastructure, at first produces an expansion of infrastructure to the urban periphery, followed by a more heterogeneous landscape, with clusters of neighborhoods with old infrastructure at the center of the city for both systems (Fig. 3 and Supplementary material Fig. 2). Of the three scenarios, Expand Access generates the largest area covered with infrastructure and a medium degree of social pressure. It also produces newer infrastructure systems compared to the Repair First scenario, but older systems than Squeaky Wheel.

Finally, the Repair First governance generates early investments in the core of the city, in neighborhoods where infrastructure is already aged. This pattern of investment persists over time, generating homogeneous infrastructure systems in terms of age across the landscape. In the long term, Repair First creates lower levels of inequality in infrastructure condition, but the most number of protests (Table 1). The Expand Access governance does not increase the area with infrastructure as much as Repair First. Though the Expand Access governance aims to provide access to a broader population by assigning greater weight to areas that lack infrastructure, over the long term, as

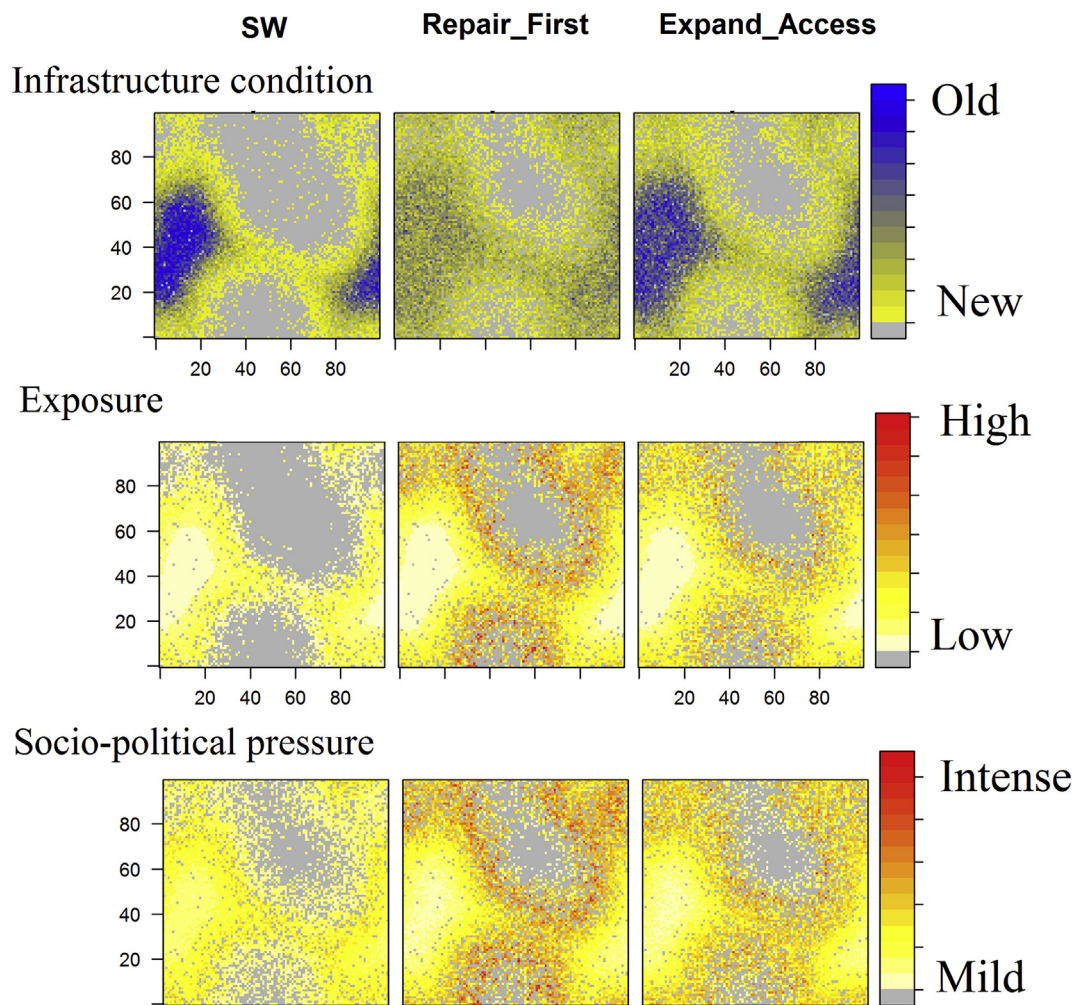


Fig. 3. Spatial patterns of vulnerability associated with water scarcity under three designed policies. The figure illustrates the differences in infrastructure system conditions, exposure, and social pressure resulting from three designed policies at the end of the simulation period. The Squeaky Wheel governance creates an old potable water infrastructure at the core and newer infrastructure at the periphery. This governance generates low levels of infrastructure expansion to the periphery and milder social pressure when compared to the other two policies. The Repair First governance maintains the newer infrastructure system conditions at the core of the urban landscape and an expansion to the periphery. Overall, this governance increases access to infrastructure at the periphery, yet it also generates more social pressure. The Expand Access governance generates a landscape with more neighborhoods with access to infrastructure systems, and a more homogeneous infrastructure age. The social pressure at the periphery is milder than in Repair First but higher than in Squeaky Wheel. Results for flood-related vulnerability are presented in the Supplementary material, Fig. S2.

the condition of the infrastructure systems decay over time, more areas become in need of repair because of the constant presence of budgetary constraints. This is in contrast to the Repair First governance, which, by focusing constantly on reducing the age of infrastructure, generates more neighborhoods covered with functional infrastructure compared to the other policies.

3.2. Governance trade-offs

Here we focus on presenting outcomes to illustrate that each governance scenario can generate trade-offs in vulnerability indicators using a graphical representation. Results from the Monte Carlo simulations illustrate the diversity of policies that can be optimal for different indicators (Supplementary material, Note 2 and Fig. 1). When comparing the designed policies (triangles in Fig. 4), we observed a clear trade-off between investing by following social pressure (Squeaky Wheel governance) vs. pursuing more technical criteria (Repair First or Expand Access policies), especially in scenarios with social pressure (Fig. 4b) and a large extent of area covered (Fig. 4c). A governance that minimizes social pressure is likely to result in problems with infrastructure age, and the reverse is also true. That is, technical policies are

more effective in reducing the age and increasing the extent of infrastructure systems. Finally, results show that investment in managing flooding-related issues can be at the expense of managing scarcity, and vice versa. These trade-offs are observed in Fig. 4, with the optimal policies that favor potable water indicators shown vs. those that favor sewage system indicators (Fig. 4a).

3.3. Thresholds and sensitivity to governance

Because we aim to convey a discussion with stakeholders about the importance of their decisions, we want to evaluate how sensitive the outcomes are to the governance scenarios in different regions of the landscape and under different budget constraints. Figure 5 illustrates the average age of the infrastructure at the end of the simulation in different regions of the simulated landscape for each of the three designed policies. The condition of the potable water system in the lowlands is highly sensitive to changes in governance. The same is not so true for the sewage system. In mid- and highland areas it is the sewer system that is more affected by these changes.

We also looked at how sensitive the results are to budget constraints. Figure 6 showed the emergence of expected and unexpected

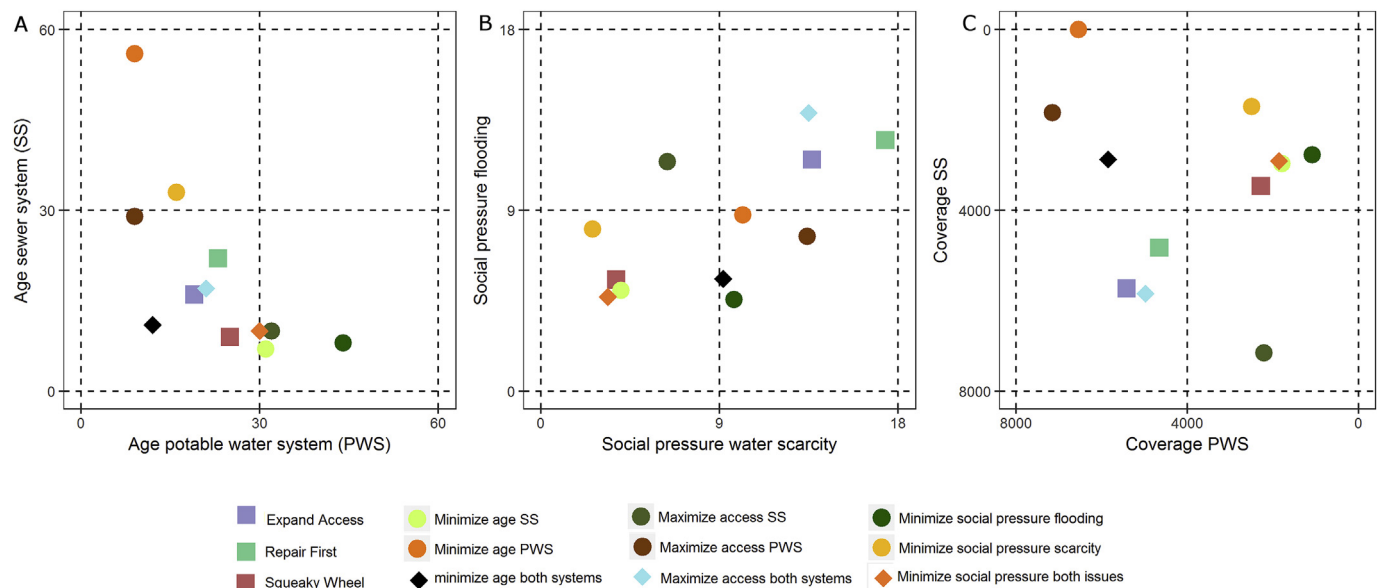


Fig. 4. Trade-offs in governance scenarios. The figure illustrates the outcome of the 12 policies for three indicators of vulnerability: city-average age of infrastructure systems (panel A), city-average social pressure (B), and the extent of functional infrastructure (C). The x-axes correspond to indicators associated with the potable water system and water scarcity, while the y-axes correspond to indicators related to the sewer system and flooding. Squares represent the three designed policies: Squeaky Wheel (dark-red), Repair First (green), and Expand Access (blue). The circles and diamonds represent optimal policies obtained after extracting best outcomes from Monte Carlo simulations. Circles for individual indicators, and diamonds for policies that optimized for both flooding and potable water. Circles in orange, brown and light orange represent those policies oriented to potable water and water scarcity indicators, and circles in green tones are for those policies associated with sewer- and flooding-related indicators. The figure illustrates the trade-off among indicators, policies, and infrastructure systems and the sensitivity of these trade-offs to the decision-makers' governance scenarios. The full range of indicators is presented in Table 1. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

non-linear patterns based on this constraint. An increase in resources positively impacts the condition of the infrastructure system by reducing the average age as resources increase (Fig. 6a, b). The figure shows that social pressure unexpectedly increases when resources for investment increase. In the process of building new infrastructure, it is

difficult to maintain the old infrastructure. This creates more risk over long-term horizons and consequently more protests (Fig. 6c, d). These patterns are less striking for the Squeaky Wheel governance scenario.

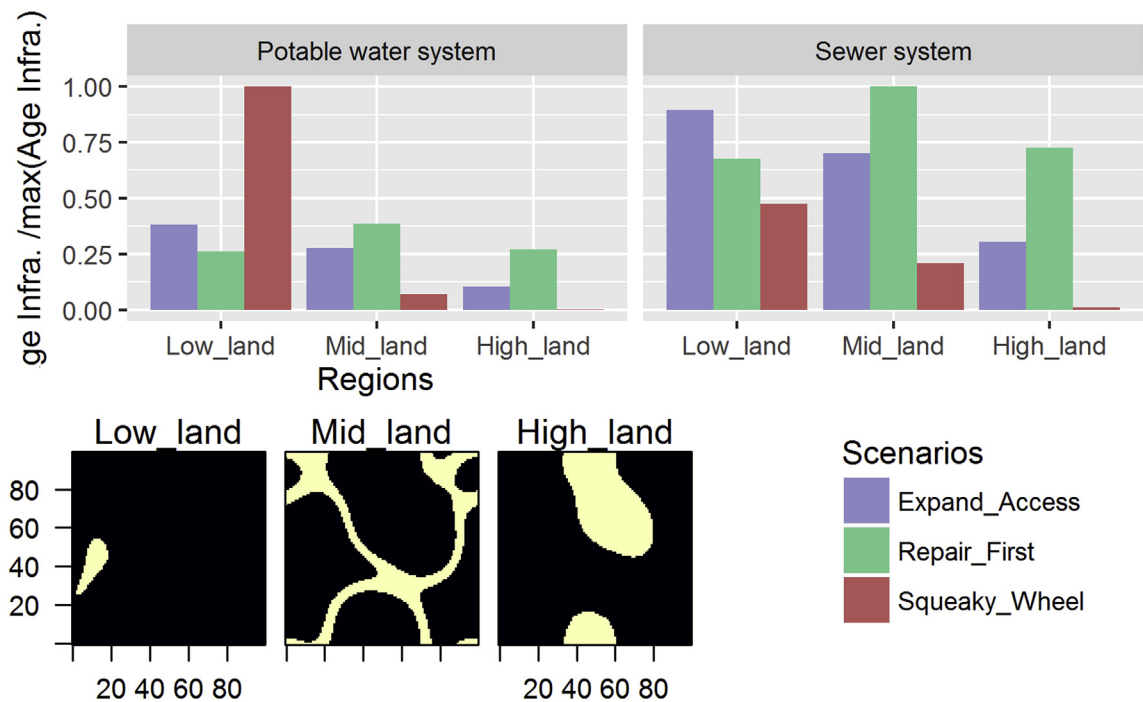


Fig. 5. Sensitivity of the condition of infrastructure to changes in governance scenario by region. The urban landscape has been divided into lowlands, highlands, and midlands to represent the sensitivity of the investment to governance scenarios by region. The average age of infrastructure relative to the maximum value observed is presented in the bar-plots at the top of the figure. The figure illustrates the geographic trade-offs of the three designed governance scenarios.

Table 1
Indicators of urban vulnerability and policy scenarios. Policies and Vulnerability Indicators.

Policy Scenarios	System/Problem									
	Sewer system/Flooding					Potable water system/Water scarcity				
	Inequality [Gini]	Exposure [events/cycle]	Social Pressure [events/cycle]	Infrastructure		Inequality	Exposure	Social Pressure	Infrastructure	
				Age	Coverage [# neighborhoods]				Age	Coverage
Expand Access	0.28	9.83	11.52	16	5731	0.28	11.83	13.66	19	5421
Repair First	0.25	10.72	12.49	22	4828	0.26	15.08	17.36	23	4656
Squeaky Wheel	0.37	4.47	5.54	9	3464	0.39	2.85	3.79	25	2284
Maximize access PWS	0.24	6.36	7.70	29	1844	0.39	11.60	13.43	9	7153
Maximize access SS	0.35	9.84	11.42	10	7153	0.27	5.18	6.38	32	2208
Minimize social pressure scarcity	0.41	6.67	8.06	33	1703	0.38	1.80	2.61	16	2494
Minimize social pressure flooding	0.28	3.55	4.56	8	2772	0.42	8.23	9.74	44	1083
Minimize age PWS	0.27	7.32	8.76	56	0	0.38	8.67	10.17	9	6543
Minimize age SS	0.38	4.02	5.02	7	2972	0.41	3.07	4.03	31	1794
Maximize access to both systems	0.24	6.36	7.70	29	1844	0.39	11.60	13.43	9	7153
Minimize social pressure both issues	0.37	3.67	4.69	10	2909	0.42	2.49	3.38	30	1860
Minimize exposure to both issues	0.37	3.67	4.69	10	2909	0.42	2.49	3.38	30	1860
Minimize age both systems	0.29	4.52	5.58	11	2871	0.40	7.70	9.18	12	5853

The outcome of the simulation are presented as indicators of vulnerability for each infrastructure system. These indicators are evaluated for the last 10 cycles of a simulation using the five indicators. The rows indicate the different policy scenarios. The first three scenarios correspond to the designed policies. The rest are the scenarios of the optimal policies associated with a particular indicator.

4. Discussion

The dynamic and spatially-explicit modeling approach presented here aimed to make explicit the linkages between decision-making and the patterns of urban vulnerability. We emphasize that this approach intends to make visible, dynamic, and transparent the social-political factors that are often excluded in vulnerability assessments. This is done by purposely endogenizing institutional agents as algorithms that simulate changes in landscape attributes. In this way, our approach offers a tool for making the dynamics of “social vulnerability” explicit and potentially collaborative (Elsawah et al., 2015).

In the stylized implementation, loosely based on the flooding and scarcity circumstances in Mexico City, the incorporation of “social pressure” as a socio-political decision criterion acknowledges that choices regarding infrastructure investment are often influenced by less technical criteria, such as preferences for specific socioeconomic groups, electoral constituencies based on voting patterns, or the need to respond to specific events with high political visibility and publicity. These criteria can steer decisions and, specifically, investment toward particular regions or groups can transform the built environment in significant ways, and in part, determining the preparedness of future generations to confront environmental hazards (Alba and Oropeza, 2014; Gramlich, 1994; Kloster and de Alba, 2007). Therefore, because the implications of these investments transcend the space and time where those initial decisions are made, it is critical to employ tools that can elicit how these actions steer the production of vulnerable populations (Eakin et al., 2016). In Mexico City, for example, protests are linked to demands related to the lack of investment in infrastructure and triggered when conditions become critical for the water system users, and this produces immediate responses that steer resources to these foci of political attention (Eakin et al., 2017). Over time this socio-political infrastructure can generate inequalities in resource distribution. Election cycles provoke social mobilizations designed to divert financial and material resources to areas with strong social organizations and voting power. This may occur at the expense of other groups that are in greater need, but perhaps less influential or organized (Aguilar and López, 2009; Kloster and de Alba, 2007). Making these

social and political forces explicit as part of decision-making is the first step to be able to evaluate the impact of such criteria on the production of urban vulnerability.

The example illustrates the trade-offs that can emerge across different indicators and optimal governance scenarios for reducing risk exposure (e.g., between flood control and water access) and improving the infrastructure systems condition (e.g., potable water and sewer systems). Trade-offs are inevitable as society seeks to control some aspects of risk at the expense of others (Janssen and Anderies, 2007). These vulnerability trade-offs are particularly prevalent in complex socio-ecological systems and “coupled human-infrastructure systems” (Anderies et al., 2016). Therefore, we must expect that decision-makers and society at large will be constantly confronted with options to invest in different alternatives. However, we often lack frameworks and specific tools with which to evaluate or justify such trade-offs (Carpenter et al., 2001, 2015; Eakin et al., 2009; Janssen and Anderies, 2007; Meerow and Newell, 2016). Our modeling approach lays the foundation to reveal the trade-offs among distinct pathways that emerge from the reinforcement of specific decisions (Wise et al., 2014), and it echoes calls for action (Acuto et al., 2018) to make these trade-offs explicit and visible (Eakin et al., 2017).

Our hypothetical example purposely simplified the biophysical complexities that influence environmental risk. By simplifying those biophysical aspects of vulnerability, our aim was to make explicit the consequences of socio-institutional decisions on the emergence of vulnerability. The hypothetical risk models presented in the example took a frequentist approach, where flooding and the exposure to water scarcity were associated with a set of biophysical, infrastructure, and socio-political attributes. Ideally, the changes in these attributes would be associated with biophysical models that simulate mechanistically the emergence of risk (e.g., global and regional climate models). However, it is important to recognize that the implementation of biophysical models at the scale of a megacity would be difficult, not to mention the inherent complexity involved with the integration of multiple models. Bayesian and frequency-based models can be instrumental in formalizing the contribution of environmental and decision-related factors to risk (Bojorquez-Tapia et al., 2019), as the information to parametrize

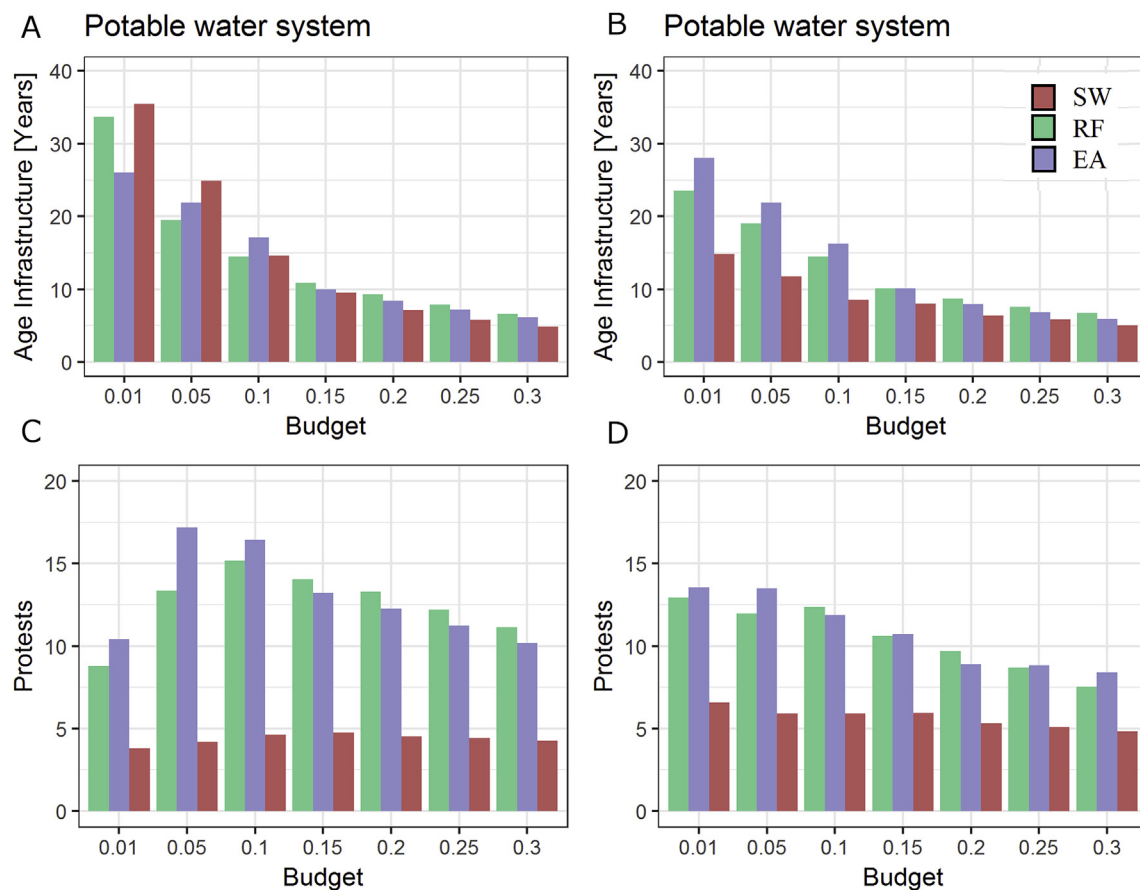


Fig. 6. Sensitivity of governance scenarios to budget constraints. Panels A and B show the average age of the infrastructure for flood control and water supply, respectively. Panels C and D show the resulting average number of protests per neighborhood in a decision cycle. The different colors represent the three designed governance scenarios (Squeaky Wheel, Repair First, and Expand Access). The condition of the infrastructure and the social pressure that emerge are sensitive to governance decisions, especially under low budgetary conditions. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

such models should be available from different sources. This perspective would allow for the operationalization of methods to include deep uncertainty surrounding the consequences of these management decisions, along with other external forces of uncertainty. It is important to note that regardless of the specific models for representing a risk, they must be used in a context in which they can serve to explore and embrace uncertainties, rather than merely providing predictions of future climate scenarios. This should lead to open and transparent discussions with stakeholders about common problems, current practices and possible ways of moving forward, using the best information available.

We recognize that it is a major challenge, scientifically and politically, to elicit the full range of political criteria and the factors that guide governance implementation. Particularly difficult are those intangible factors often associated with cultural bias within organizations and institutions. Formal institutional or agency perspectives may tend to highlight more socio-political criteria, while low-to mid-level managers may focus on more technical criteria, obfuscating these more intangible “soft” decision metrics. Close collaboration at different hierarchical levels of institutions is critical for building trust and revealing the inner workings of decision processes (Bojórquez-Tapia et al., 2011, 2005). We propose multi-criteria decision analysis to elicit the set of criteria and actions to represent agents’ decisions (Bojórquez-Tapia et al., 2019; Bojórquez-Tapia et al., 2011; Meerow and Newell, 2017), but other soft modeling techniques and mental model elicitation could be instrumental as well (Checkland and Poulter, 2006; Elsayah et al., 2015; Jones et al., 2011; Leitch et al., 2015; Morgan et al., 2002; Pahl-Wostl, 2010, 2008, 2003). Coupling these techniques with

biophysical and infrastructure reliability and vulnerability models (Kabir et al., 2014; Manson, 2006; Mendoza and Martins, 2006) should provide opportunities for researchers to help elicit the feedback that shapes decisions in space and time, thus enhancing transparency and accountability. Comparing and discussing such coupled models should provide valuable information that can be used to reveal hidden vulnerabilities only apparent when considering the coupling, emergent patterns, dilemmas, and trade-offs specific to each governance scenario.

5. Conclusion and future directions

We provide a modeling framework to operationalize and visualize the outcome of vulnerability that emerges from socio-political, and institutional decisions. The framework emphasizes making visible the patterns of vulnerability associated to dominant actors and their ideas about risk, environmental and resource management and the causal effect between them.

Our approach provides a basis for interacting with stakeholders and decision-makers by proposing outcome analyses that can foster self-evaluation and reflection on the socio-political factors behind the vulnerabilities of cities, providing new avenues for transdisciplinary engagement with different sectors of society. The modeling approach, therefore, substantiates calls for focusing on the endogenous, social-political dimensions of risk in vulnerability assessments.

An empirical demonstration of the method in Mexico City linking biophysical models (i.e., hydrological, infrastructural, climatic, land-use models) with empirically-based information about actors’ decisions

and their motivations is underway. By incorporating the coupling between biophysical processes, managerial decisions, and political forces, the framework can help managers and decision-makers to navigate the complexities of urban management.

Author contributions

L.A.B.T., H.E., and M.A.J. conceived the research; H.E., L.A.B.T., and M.A.J. formulated the framework; A.B. L.A.B.T. and M.A.J. formalized the framework, and A.B. developed the NetLogo example and conducted the numerical analyses. All the authors contributed to the final writing of the manuscript.

Competing financial interests statement

All the authors declare not having any competing financial interests.

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Appendix A. Supplementary material

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